PALEOCLIMATES AND THE CHANGING ENVIRONMENTS OF ANZA-BORREGO

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You don't need a weatherman to know which way the wind is blowing.
—Bob Dylan, 1960s

Introduction: Climate, Weather, and Gravity

"Climate" is defined as the characteristic weather of a region, averaged over some significant time interval. "Weather" is what we see reported on the evening news: temperature, barometric pressure, and humidity of the air; direction, speed, and motion pattern of the wind and the waves; and the form and quantity of precipitation.

Earth's climate seems to be in a warming phase today, as is evidenced by melting polar icecaps and record high summertime temperatures. Climate changes have occurred both in long-term trends lasting tens of millions of years and in relatively rapid cycles over as little as a few thousand years (such as during some of the glacial periods of the past two million years. Although tectonic events and occasional disastrous impacts from outer space may influence our climate, its major determinants are the astronomical characteristics of the solar system. Weather and climate on Earth are probably somewhat affected by tiny variations in solar radiation, such as those associated with the eleven-year sunspot cycle. However, the main factor that dictates how much energy we receive from the Sun is our distance from it.

Our solar system is a spinning, wheeling arrangement of planets and other bodies circling a star—the Sun—at various distances. The planets turn on axes of rotation as they move around the Sun in more or less circular paths called orbits. Several planets have satellites of their own, moons, which orbit around them. Every body in the solar system acts on every other body through the force of gravity, establishing and then subtly perturbing the complex planetary motions. This has profound implications for climate.

Both the axial orientation and the orbital motion of the Earth affect the climate by bringing the planet and different regions of it alternately closer to and farther away from the Sun. The axis of Earth's rotation is tilted, not vertical, to the plane of its orbit. As the Earth moves around its orbital path, it passes through a point at which the Northern Hemisphere is maximally tilted toward the Sun. On this date, Earth experiences the longest day of the year, which is the summer solstice. Six months later, or 180° through the orbit, the Northern Hemisphere is maximally tilted away from the Sun and we experience the winter solstice. This cyclic variation in received solar energy is what causes our annual seasonal weather patterns.

Currently, the axis of Earth's rotation is tilted about 23.4° from the vertical, but this is not a fixed angle. Over time, the axis very slowly increases and decreases its tilt from 24.5° to 22.2° (the tilt is slowly decreasing today). The tilt cycle requires 41,000 years to complete a full cycle. While the Earth's tilt is slowly changing, the direction the axis points to the heavens slowly shifts such that in the not-too-distant future, Polaris will no longer be the pole star. This axial direction change describes a wobbling motion such that the geographic poles trace circular paths in opposite directions. This effect, called precession, is similar to the motion of a spinning top as it slows. It requires 25,700 years for the wobble to move completely around the cycle.

The time measurement from solstice to solstice, known as the "tropical year," is the basis for our civil calendar. However, there is another way to measure time. As the Earth orbits the Sun, the Earth-to-

Sun distance varies because the orbit is slightly elliptical rather than circular. Once each year, the Earth makes its closest approach to the Sun, called perihelion (from the Greek for "near the Sun"). (Aphelion is the point farthest from the Sun.) The time measurement from perihelion to perihelion, known as the "anomalistic year, is approximately twenty-five minutes longer than the tropical year due to a combination of the effects of precession of the axis of rotation, which causes the exact timing of the solstice to vary from year to year, and small orbital perturbations. The date of perihelion thus occurs later each year, regressing with respect to the solstice. Perihelion currently occurs only two weeks after the winter solstice. The perihelion regression cycle, combined with the axial wobble, creates a dominant cycle near 23,000 years as the date of perihelion progresses through the entire tropical year.

A larger orbital fluctuation is the 100,000-year "eccentricity cycle," during which the elliptical shape of Earth's orbit becomes slowly more or less pronounced, varying from nearly circular to about three times present values. The difference between aphelion and perihelion distances is actually quite small, currently about 3 percent, not enough to cause a pattern of seasonal variation but capable of affecting its severity. During epochs of large eccentricity, the effect of the perihelion shift cycle is magnified.

The 100,000-year eccentricity cycle, the 41,000 year obliquity cycle, and the 23,000 year perihelion regression cycle are caused by gravitational interactions not only involving the Sun, Earth, and Moon, but also Jupiter and Venus. Together the cycles are known as Milankovitch cycles, after Milutin Milankovitch, a Serbian engineer who worked out the model and its mathematics during the 1920s and 1930s. Although Milankovitch cycles are well grounded astronomically, the relationship of long-term climatic variations to astronomic causes is not yet completely laid out, most notably lacking a clear mechanism by which the 100,000-year eccentricity cycle exerts a direct effect on climate. However, the potential is there for a "perfect storm" conjunction of all three cycles to tip us into dramatic climate change.

Other modifiers may play a leading role in amplifying orbital effects as the various ways in which the Earth receives, reflects, stores, and utilizes its solar radiation allotment interact to determine the climate of a given region. The distribution of water, ice, rock, and vegetation on the Earth's surface affects the planet's tendency to reflect rather than absorb sunlight, a phenomenon called albedo. Long before there were power plants and automobiles, volcanoes would periodically spew high loads of particulates and gases into the upper atmosphere, temporarily changing the way solar energy reached the surface of the Earth. They still do, causing major short- and long-term weather changes. Patterns of air and water circulation become established, fixing regional climates for a while. Sea levels rise and fall depending on the amount of water frozen into ice sheets and glaciers. Islands rise and coalesce into land bridges, altering the patterns of ocean currents. Mountain ranges are pushed up to wind-blocking heights by deep tectonic forces, then erode down again. These Earth processes also change the chemistry of the atmosphere, as crystalline rock reacts with carbon dioxide, trapping and burying this greenhouse gas in new sediment, thus cooling the planet.

Paleoclimate Inferences from the Fossil Record

Paleontology opens windows on the past, a major theme of this book. The fossil record offers broad perspectives on ancient climates, environments, and habitats that may be made more definitive by "climate proxies," as discussed in the following section.

The climatic and environmental story told by the rocks and fossils of the Park begins in the later Miocene with the development of the ancestral Gulf of California about 7 million years ago. This marine

environment was warm and tropical, with affinities to the modern Caribbean Sea. The oldest sandstone strata of the Imperial Group were being laid down around and under the warm, clear waters of the Imperial Sea. Anza-Borrego was part of the Tertiary Caribbean Province, an unbroken tropical region encompassing the Caribbean Sea, the western Gulf of Mexico, and the equatorial eastern Pacific Ocean. Many of the clams, snails, and corals found fossilized in the Imperial Group have affinities with both fossil and living Caribbean species (see Deméré, this volume).

This sunny picture began to change around 5 million years ago, at the very end of the Miocene. Locally, the ancestral Colorado River started to build its massive delta at the head of the proto-Gulf of California, rapidly depositing claystones and siltstones from its turbid flow on top of the older sandstones. The very rapidity of the erosion process speaks of a period of increased precipitation in southwestern North America. Although the latest Miocene (6.5–5 million years ago) was marked by the cooling at high and middle latitudes that is associated with global marine regression due to Antarctic ice sheet expansion, the earliest Pliocene was a period of warming temperatures (Kennett, in Vrba et al, 1995). By the early to middle Pliocene (4.0–2.6 million years ago), the Anza-Borrego region was a floodplain near sea level, still receiving the sediments of the Colorado River, whose delta had already walled off the upper part of the proto-gulf.

Fossil hardwoods from these deltaic deposits reveal that the river floodplain was occupied by a temperate woodland community consisting of bay laurels, walnuts, avocados, cottonwoods, willows, ashes, buckeyes, and palms. This flora is an excellent indicator of wet soil and permanent water in a moderate but four-season climate with annual rainfall of 38–62 cm (15–25 in.) mostly in the winter or spring, and temperatures ranging from 15° to 80° F (see Remeika, this volume, "Ancestral Woodlands").

Ostracodes are microscopic arthropod crustaceans commonly called water fleas or mussel shrimp. Their numbers in freshwater lakes and ponds will bloom under favorable conditions. Fossil ostracode abundances in the 1–2 million-year-old Hueso Formation in the Vallecito Creek-Fish Creek basin indicate significantly higher annual precipitation. Peak abundances appear to fluctuate with a 100,000-year Milankovitch cycle (Cosma, 2002).

The presence of at least five species of fossil tortoises and turtles in the Hueso and Ocotillo deposits suggest that the region had warm winters, cool summers, and enough precipitation to maintain permanent bodies of water. The presence of the giant tortoise suggests that winters never dropped below freezing. The record of Neotropical iguanid lizards further supports this picture. However, the appearance in the fossil record of spiny lizards, alligator lizards, skinks, ground lizards, and whiptails at about 2.5 million years ago speaks for the spread of grassland and savanna habitat in the region (see Gensler and others, this volume).

The fossil birds of the Park, mostly water birds and perching birds, range from mid-Pliocene to mid-Pleistocene age (3.5–0.5 million years ago) and also indicate a setting of lakes, ponds, and streams during this period (see Jefferson, this volume.)

Several groups of large animals arrived early and stayed late in the region from late Miocene through the close of the Pleistocene age. Among these were the camelids. This group apparently attained its greatest diversity in response to the emergence of open grasslands. They exhibit a number of adaptations, mostly of the limbs, gait, and teeth, which facilitated a highly cursorial, mostly grazing mode of feeding with variations among coexisting species that would have enabled them to partition resources effectively. The group had prolonged success, surviving and thriving through many climate shifts in what

became an increasingly arid environment. They became extinct in North America about 11,000 years ago, along with most of the other large animals.

Another group of large animals that arrived early and stayed late was the giant ground sloths (see McDonald, this volume, "The Ground Sloths: Invaders from South America"). These xenarthrans originated in South America and entered North America in three stages across the slowly developing Isthmus of Panama beginning in the late Miocene around 9 Ma. The first group to arrive was the megalonychids. They were browsers more dependent on forest habitat than the other two sloth groups, and were more abundant in the eastern United States than the western, where their distribution was likely to follow watercourses and riparian vegetation. This group is represented by several species of *Megalonyx* from Anza-Borrego. The second group was the mylodonts, which are represented in Anza-Borrego by *Paramylodon harlani*. Members of this group have dental and limb adaptations suitable for grazing or mixed feeding in country that is more open. The third group was the megatheriids, which are represented locally by *Nothrotheriops,* the Shasta ground sloth. These appear to be adapted for an eclectic diet and survival in a more arid or even desert habitat.

Each of the three groups had a different preferred habitat. Although they may occur jointly in a North American fauna, it is thought that this only occurred at the contact area, or ecotone, between their preferred habitats. A diversity of habitats prevailed here during the Pliocene and much of the Pleistocene even as the overall climate became more arid with the development of the rain shadow of the Peninsular Ranges after around 1.5 million years ago (See McDonald, this volume).

Anza-Borrego's more than 3,800 identified small mammal fossils include a variety of both warm-adapted taxa such as the cotton rat and cool-adapted animals such as lemmings and voles (see White and others, this volume). Through the middle part of the record, these forms are found in the same strata. This makes it difficult to draw conclusions about paleoclimates during this time. Conditions may have varied or shifted back and forth on a scale that is not possible to resolve from the fossil record. However, some trends do emerge. Many of the small mammals found here as fossils had affinities for warm, moist, tropical environments, more so in the older levels of the Hueso. However, a fair number of the taxa represented are thought to have preferred a cooler environment, with seasonal variation even including winter frost and snow. Two cool-adapted forms, *Eutamias* the chipmunk and *Peromyscus* the white-footed mouse, make their first appearance about 3.3 million years ago, suggesting a shift toward a cooler climate at that time (see White and others, this volume).

Vivid as they can seem to the active imagination, these snapshots and action sequences are only limited views of the paleoclimates of Anza-Borrego, rough guides to their history. They do not tell us how different climatic regimes came to exist in this part of the world or by what means and how rapidly or slowly the region transformed from one kind of climate to another. The history of climate as revealed solely by the evidence of fossil assemblages is analogous to the evolutionary and geologic story told by relative dating methods (see Cassiliano, this volume).

How Can We Know What the Climate Was Like Millions of Years Ago? Climate Proxies

In order to generate a more meaningful narrative, including accurate descriptions of the ancient climates and their meteorologic parameters, it is necessary to devise ways of measuring *indirectly* the important variables that we have no *direct* way to measure. There are a number of such methods, known as "climate proxies," in use and in development (Bradley, 1985). Residual biological and chemical evidence

left in the rocks and fossils can be analyzed and measured with modern techniques. The results of these analyses can be precisely correlated with the specific values of some climatic variables. In other words, they are proxies or "stand-ins" for the non-directly-measurable variables. Examples of successful climate proxies include the stable isotopes of oxygen and carbon.

^{18}O and ^{16}O are naturally occurring, nonradioactive isotopes of oxygen that occur in nature. These isotopes are found in molecules such as water (H_2O) in temperature-dependent proportions as the molecule undergoes the cycle of precipitation and evaporation. Compounds containing oxygen will have an oxygen isotope ratio that reflects the oxygen isotope composition of the water at the time the compounds formed. The ratio of ^{18}O to ^{16}O ratio in meteoric water (e.g., rain), generally presented in 'delta notation' relative to an international standard ($\delta^{18}O$), is very sensitive to mean annual temperature and the amount of evaporation relative to precipitation. Delta values decrease (move in a negative direction) as the climate cools and becomes wetter. These values increase (become more positive) as the climate warms and gets drier. The shells, bones, and teeth of animals, often fossilized, contain abundant oxygen in compounds such as carbonates and phosphates, which are synthesized by the animal's cells from ingested water.

The stable, nonradioactive carbon isotopes ^{13}C and ^{12}C are sorted or fractionated in characteristic patterns by plants using different biochemical pathways of photosynthesis. A stable carbon-containing compound, such as the mineral hydroxyapatite ($Ca_5[PO_4 CO_3]_3[OH, F, Cl]$) that is contained in the tooth enamel of herbivores, will reflect the carbon isotope patterns of the plants in their diet. This is because the relative proportions of the carbon isotopes from the ingested plants are incorporated directly into the animal's bones and teeth. These body parts are then found as fossils that can be chemically analyzed. The ratio of ^{13}C to ^{12}C ($\delta^{13}C$ when compared to an international standard) serves as a proxy for the relative proportion of the different types of plants in the diet. The $\delta^{13}C$ value in vegetation is lower (i.e., there is less ^{13}C) in C3 plants (the grasses, trees, and shrubs of cooler, wetter climates), which make a three-carbon intermediate molecule during photosynthesis, than in C4 plants (the grasses of more arid climates, which have more ^{13}C) that manufacture a four-carbon intermediate sugar. Since different plants are associated with distinct climatic conditions, the carbon isotope composition of bones and teeth is a proxy indicator of climate.

Determining the mechanisms responsible for variations in proxies like stable oxygen and carbon isotopes deepens our understanding of their actual relationship to the long-vanished climates and biological systems they represent. By applying proxy techniques to modern specimens under known conditions, the paleoclimatologist can achieve increasingly accurate climate-proxy calibration, something akin to the way in which we use the skeleton of a modern animal to help us understand the fossil bones of its remote ancestors. In addition, and most importantly, correlating a good proxy climate measurement with a well-constrained date for a specimen using modern absolute dating methods can help us to reconstruct both the nature and the history of an ancient climate.

What Do Fossil Horse Teeth Have to Do with Paleoclimates of Anza-Borrego?

The relative proportions of the oxygen isotopes ^{18}O and ^{16}O of the calcium carbonate ($CaCO_{3)}$ in shells of fossil microorganisms that make up much of the bulk of marine sediments has been studied since 1947 (Urey, 1947, 1948) to determine the history of ocean temperatures. Such studies have yielded valuable information about the sequence of glacial periods during the Pleistocene. Recently this method was applied to a collection of well-dated fossil horse teeth from Anza-Borrego, ~2.9 to ~0.8 million-year-old (Brogenski, 2001). *Equus* remains are the most common and abundant large mammal from the Anza-

Borrego Desert (See Scott, this volume). Thus, a study of their teeth from the Hueso Formation could yield a continuous proxy record of climate extending over more than two million years, including the Pliocene-Pleistocene boundary.

Fossil teeth are ideal for geochemical analysis for much the same reason that we find so many of them: They are quite resistant to abrasion and weathering. Tooth enamel is composed of an extremely hard, polished, nonporous form of the mineral hydroxyapatite ($Ca_5[PO_4\ CO_3]_3[OH, F, Cl]$), the basic substance of both bones and teeth. The enamel surface has low porosity and large hydroxyapatite crystals, leaving less than 1% of the atoms on the crystal surface of a tooth available for chemical reactions. Thus, the proportion of oxygen isotopes fixed in the phosphate and carbonate groups of the hydroxyapatite when the tooth is formed remains stable over very long time periods, continuing to reflect the geochemistry of the animal's drinking water as it changed with evaporation and precipitation. Similarly, the proportion of different carbon isotopes in the enamel is a stable proxy for the proportions of different types of plants eaten by the animals.

Brogenski (2001) analyzed the oxygen and carbon isotope ratios in a total of 28 fossil horse teeth from the Park, each with well-constrained ages ranging from 2.9–0.8 million years ago (see Cassiliano and Remeika, this volume). Each specimen was examined both in a serial sampling method, which collected enamel at 6 mm (1/4 in.) intervals from root to crown, and in a bulk sampling method, which collected enamel from the entire length of the tooth. The serial samples were used to determine $\delta^{18}O$ and $\delta^{13}C$ in the enamel layers of each specimen, demonstrating seasonal variations within a single tooth. Analysis of the bulk samples provided evidence for long-term climatic change over the 2.1 million years represented by the specimens.

Ninety separate samples of tooth enamel were analyzed by a complex process of extraction, purification, and mass spectrometric determinations of the isotope ratios for both the carbonates and phosphates of the hydroxyapatite. Results for both oxygen and carbon isotopes were plotted against time. Seasonal variations of as much as 2-3% in isotopic values were seen in the serially sampled enamel, with greater variability in the oldest sample at 2.92 million years ago and less seasonality in the samples across the Plio-Pleistocene boundary at 2.18 and 1.06 million years ago. Clear trends were evident in the long-term (bulk samples) data.

High $\delta^{18}O$ values (enriched in ^{18}O) near 2.9 million years ago decreased gradually between 2.9 and 2.0 million years ago, suggesting a change from warm/dry conditions to a cooler/wetter climate during the latest Pliocene. Then, near the Plio-Pleistocene boundary at 1.9 million years ago and into the more recent Pleistocene, the oxygen isotopic values increased to those similar to 2.9 million years ago, suggesting an abrupt return to a warmer/drier climate. $\delta^{13}C$ values, however, showed a distinct shift at the Plio-Pleistocene boundary, indicating a change from C4 (more arid vegetation) to C3 (vegetation requiring wetter conditions) plants, which would suggest a transition to a cooler and/or wetter climate. This apparent paradox is an intriguing mystery that research scientists are currently studying. While we do not have a clear explanation yet, several geological and oceanographic changes were occurring at this time that could provide clues to explain this conundrum.

The late Pliocene and Plio-Pleistocene boundary period between ~2.7 and ~2 million years ago was a time when marine fossil evidence shows that ocean temperatures cooled substantially, and in the Northern Hemisphere, the Greenland ice sheets grew for the first time. It was also a time of major tectonic change, with the final closure of the Isthmus of Panama producing the continental pattern that we see today. In all likelihood, the final closure of Panama during the late Pliocene initiated the transformation of ocean and

atmospheric circulation patterns into the patterns that exist in the twenty-first century. The oxygen isotope data obtained by Brogenski (2001) suggests that horses living in the vicinity of Anza-Borrego were drinking water that had experienced elevated evaporation. However, the carbon isotope data suggests that the grasses the horses were feeding on required more rainfall to thrive. Could the closure of the Isthmus of Panama, a change in ocean and atmospheric circulation, and the glaciation of Greenland have conspired in some complicated way to create conditions that can solve this contradictory data set? We can only wait and see what answers next come—quite literally from the horse's mouth.

Conclusions

Climate is a complex system, the sum of many mechanisms that interact in obvious and unobvious ways. Life and its evolution always have and always will depend intimately on climate. Understanding the climate of our planet, how it changes from one state to another or maintains long-term stability, is of crucial importance to our species. The challenging puzzle of how the climate of the Anza-Borrego region evolved to its present state, including an understanding of the stages and transitions it passed through over the eons, requires more than one key for its full solution.

Some of those keys surely reside in cabinets and drawers full of fossil specimens. The fossil collection, neatly prepared, curated, dated, stored, and catalogued, is not merely the raw material for exhibits. It is an enormous natural archive of environmental data containing more information than we currently know how to extract. As Colleen Brogenski says in the introduction to her 2001 thesis, "The fact that the Anza-Borrego Desert State Park stratigraphic sequence represents the longest continuous Plio-Pleistocene sequence in the United States, and is one of the few North American sections in which late Pliocene and early Pleistocene faunas occur in superposition, makes it an ideal section for the study of biological and ecological change at geologically short intervals." This, combined with abundant evidence of concurrent local tectonic and hydrographic changes, invites the development and confirmation of models for the processes that occurred here.

It is interesting to reflect on the early paleontologists who combed dry washes under a blazing sun to collect many of the fossil horse teeth that are being studied today. At the time, those intrepid rock hounds could not have anticipated the intricacies of stable isotope mass spectrometry nor the wealth of environmental information that was locked within the small fragments of horse teeth they picked up. Even today, it is hard to imagine that the microchemistry of a newly exposed fossil tooth could hold the secret to the mechanisms responsible for climate change in the Park two million years ago. Who can say what tools will be available to researchers ten or fifty years in the future, or what new information might be waiting to be deciphered from the bones and teeth of long-dead organisms that roamed the region in the distant past?

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